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Morphologic Asymmetries at Entrances to Tidal Inlets

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PURPOSE: The Coastal and Hydraulics Engineering Technical Note (CHETN) herein discusses selected morphologic symmetries of ebb shoals and channels at tidal inlets with implications for maintenance of navigation channels and sediment bypassing to the adjacent beaches. Much of the information contained in this Technical Note was developed from a database created by the Coastal Inlets Research Program (CIRP) and may be found at *http://cirp.wes.army.mil/cirp/cirp.html*.

BACKGROUND: Navigational improvements will alter the morphology of an inlet and may have unintended consequences for channel maintenance, integrity of the jetties, and natural bypassing to the adjacent beaches. This Technical Note examines the characteristics of selected symmetries in morphological forms at inlet entrances and presents empirical quantitative relationships for their prediction. Possible applications of this information include:

a. Formulation of sediment budgets at inlets, where detailed sediment pathways are required.

b. Determination of the predominant (net) direction of longshore sediment transport.

c. Determination of the natural causes of entrance channel migration and realignment (both for maintenance of existing channels and for modification of channel alignment).

d. Consequences of construction of or modifications to jetties, such as alteration of sediment pathways.

e. Understanding and estimation of the locations areas of erosion and accretion near inlets.

f. Guidance on effective areas of placement of dredged material for benefit of the down-drift beaches.

Asymmetries in the morphology of ebb-tidal shoals (also termed ebb-tidal deltas or entrance bar) and orientation of the entrance channel are produced by both dynamic and static factors. Dynamic factors include the magnitude and direction of net longshore sediment transport, tidal prism, relict ebb shoal, offshore extent of the ebb jet, riverine sediment supply, flood shoal evolution, dredging of the channel, and wave refraction and diffraction over the offshore bathymetry and ebb shoal. Static factors include the locations and configurations of jetties, offshore and nearshore bathymetry, size and shape of the back bay, and constraints as imposed by the local geologic structure such as hard bottom.

The asymmetric inlet morphology at East Pass, FL, is shown in Figure 1, as inferred by the pattern of breaking waves. The ebb shoal in the broad sense is comprised of the ebb shoal proper, the updrift and downdrift bypassing bars, and the attachment bars. The ebb shoal proper forms primarily in the stream of the ebb jet, whereas formation of the bypassing bars owes more to wave action and wave-induced currents. The attachment bar develops from material bypassed around the ebb shoal complex, either arriving to or leaving from the shore. The attachment bar is sometimes called the "tie-in" or "weldment" area. In the following, the terminology "ebb shoal" refers to that portion of the ebb shoal complex located within the ebb jet. (Kraus 2000) The combination of the ebb shoal, bypassing bars, and attachment bars is termed the "ebb shoal complex." For the following discussion, it is convenient to define "inlet edge," labeled by red dots in Figure 1, denoting the location where land and water join at the point of land encroachment into the inlet. Two inlet edges exist, one on either side of the inlet. If an inlet is stabilized with jetties, the inlet edges are located at the intersection of the shoreline and jetty.

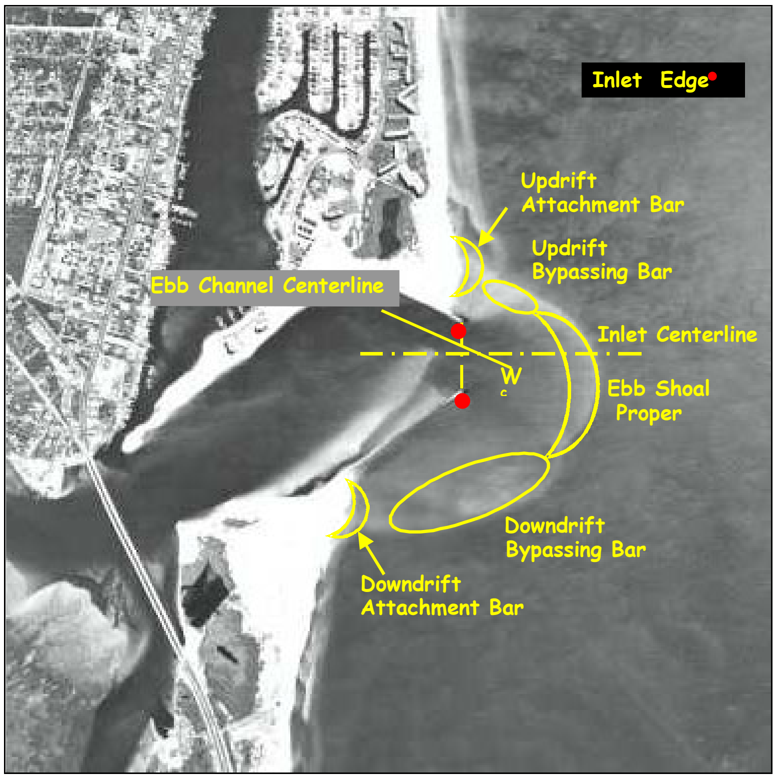

Figure 1. Inlet entrance morphology, East Pass, FL, 1990

An idealized ebb shoal complex has an arcuate form, exhibiting symmetry with respect to the entrance channel, a phenomenon consistent with turbulent jet theory. Figure 2 is a definition sketch of the measurements discussed in this Technical Note that were made from interpretation of aerial photographs. A more symmetrically shaped ebb shoal would tend to form if the left- and right-directed longshore sediment transport rates were equal, the navigational channel dredged straight out, and the main static factors of back-bay configuration, jetties, shelf bathymetry, and geologic structure symmetric across the center line of the inlet. Morphologic features and an inlet channel center line that deviate from the ideal situation are categorized as asymmetrical.

In Figure 2, the variable L represents the distance from the shoreline (which was identified as the water-beach interface for each individual measurement) to the seaward-most point of the ebb shoal. The quantity W_c is the channel critical width, defined as the narrowest point between the two landmasses on either side of the inlet. The variables W_{A1} and W_{A2} represent distances to the updrift and downdrift attachment bars (where the bypassing bars tie in to the shore), respectively.

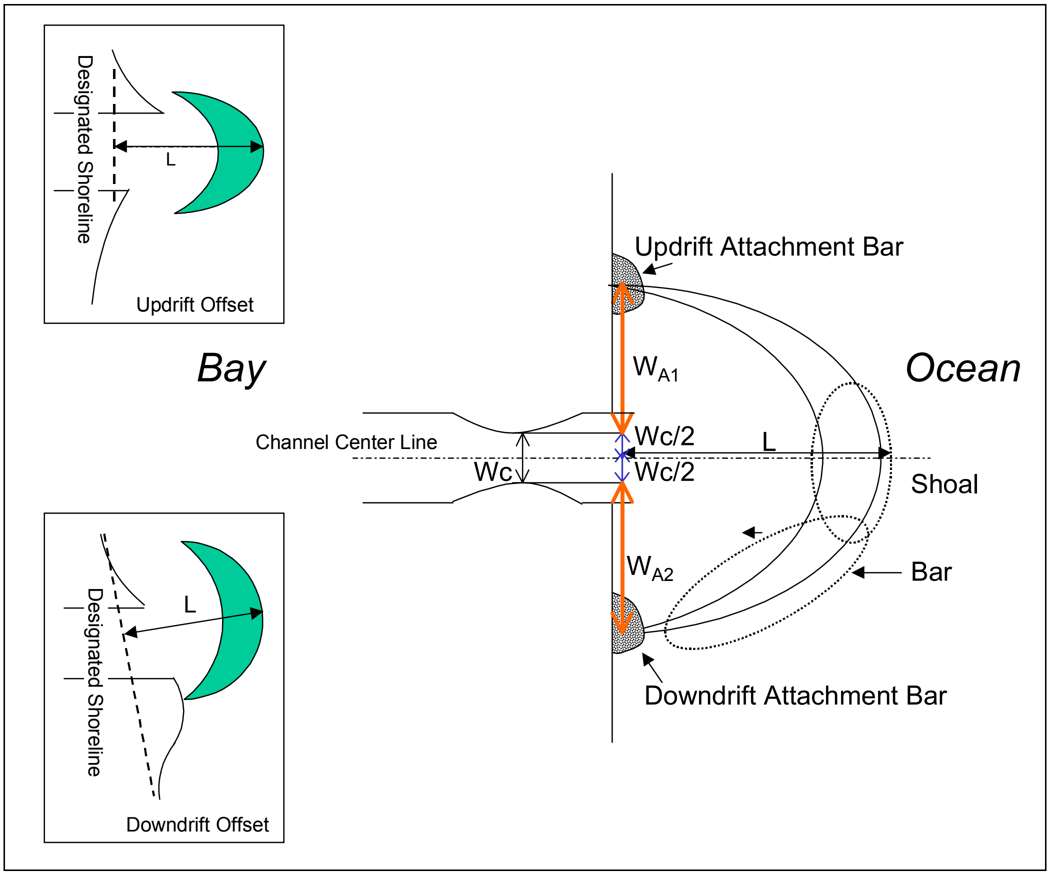

Figure 2. Symmetric ebb shoal with definitions of terminology used in measurements

The inset diagrams in Figure 2 represent the downdrift and updrift shoreline position offsets. The shoreline, which defines the horizontal coordinate in the measurements, has been taken as a line between the trends in updrift and downdrift shorelines. The line has been drawn to connect the shorelines sufficiently far from the inlet to define a more regional trend. Measurements from inlets with identified offsets were made in the same way as those with more uniform shorelines. At inlets with two jetties, jetty length did not enter the measurement process. The jetties may alter the shoreline position, in which case the preceding procedure was applied for defining the shoreline trend.

Identification of the net direction of transport, determining which shoreline lies updrift and which downdrift, is one of the first steps in applications such as development of a sediment budget, bypassing requirements and, possibly, the alignment or realignment of the entrance navigational channel. The direction of net longshore transport can usually be determined by interpretation of the shoreline signature in aerial photographs. Impoundment and erosion at jetties, growth of spits, asymmetry in the ebb shoal complex, orientation of the channel, and the existence and location of attachment bars allow inferences of net transport direction to be made. Caution must be taken to account for processes that may not be straightforward. Examples of confounding processes are changes in shoreline orientation, which change the direction of transport locally; impoundment in the downdrift shadow region of a jetty, which may make the downdrift side appear as an updrift side; seasonal sediment drift reversals (Oertel 1975); and changes in the back bay that might realign the channel. Stauble and Morang (1992) give additional information on determining net drift in complex systems.

SAND BYPASSING PROCESS: Sediment bypassing paths control much of the geomorphic asymmetry at inlets. The natural mechanism of sediment bypassing from the updrift shoreline to the downdrift shoreline through the ebb shoal complex is significant because it mitigates possible erosion downdrift of the inlet. Bruun and Gerritsen (1959, 1960) described sand bypassing at inlets and classified the ease of navigability through the prominence of an entrance bar (ebb shoal complex) in the channel. The parameter introduced for this classification r is defined as

$$r = P / M_{tot} \tag{1}$$

where P is the tidal prism (amount of water passing through the inlet during half a tidal cycle, typically during spring tide), and M_{tot} is the average annual longshore transport at the inlet. Therefore, M_{tot} is equivalent to the gross longshore transport rate at the inlet multiplied by 1 year. Inlets with a value of $r > 150$ (approximate) tend to have stable, deep channels and are poor "bar bypassers" from updrift to downdrift, whereas inlets with $r < 50$ (approximate) tend toward closure and are good bar bypassers.

Kraus (2000) quantified the growth of the ebb shoal and sediment bypassing rates from the updrift shoreline to the downdrift shoreline, assuming continuous transport. The model also predicts the delay in sediment transfer from the updrift shoreline to the downdrift attachment bar and is compatible with the concepts of Bruun and Gerritsen (1959, 1960). Guidance on the symmetry of the inlet ebb shoal complex involved in the bypassing is provided in the following sections.

The processes envisioned in the preceding formulation are considered as being primarily continuous. Gaudiano and Kana (2001) found that local sediment accretion on South Carolina shorelines is also associated with event-based bypassing in which a portion of the ebb shoal breaks off and moves on to the shore. Although episodic in nature, the bypassing occurred over a sufficiently long time interval, i.e., over a long averaging interval, that this bypassing might be modeled as a semicontinuous process. Temporal changes in inlet asymmetry are discussed in the following paragraphs.

IDENTIFICATION OF ASYMMETRIES: The outlines of ebb shoals in Figure 3 were digitized from the wave-breaking patterns observed in aerial photographs and plotted to determine representative shapes these shoals may take. The shoreline served as the baseline for the x-axis, and the inlet center line (Figure 1) served as the y-axis with positive values occurring downdrift of the origin and offshore. In the figure, positive x values (to the right of the origin) indicate normalized distance downdrift, and negative x values (to the left of the origin) indicate normalized distance updrift. Alignment of the digitized ebb shoal outlines to a common origin allows comparison of the offshore and alongshore extents of the shoal. The measured offshore and alongshore distances were normalized by their respective minimum or critical width of the inlet to obtain comparisons independent of the width of the inlet itself (inlet width varied from 0.25 to 1.7 km). Nearly symmetrical shapes of the ebb shoal complex outline as well as asymmetric shapes can be identified, showing wide diversity.

Relationships among forcing variables at tidal inlets and inlet asymmetry indicators were developed through examination of 108 tidal inlets in the United States to aid in the analysis of ebb shoal outlines as shown in Figure 3. The values for three indicators of ebb shoal asymmetry as determined from nautical charts and aerial photographs are presented. The asymmetry indicators are as follows:

a. Distance to the updrift point where the ebb shoal complex attaches to the shoreline (labeled W_{A1} in Figure 2).

b. Distance to the downdrift point where the ebb shoal complex attaches to the shoreline (labeled W_{A2} in Figure 2).

c. Distance of the offshore extent of the ebb shoal measured from the shoreline (labeled L in Figure 2).

Estimates of error can be made for the process of interpretation of the asymmetry indicators. Stauble (1998a) discusses more accurate procedures. The distance to the farthest offshore extent of the ebb shoal complex was measured from the water-beach interface. The location of the shoreline depends on the tide level at the time the photograph was taken (see Kraus and Rosati (1998) for discussion of interpretation of shoreline position). An additional source of error is associated with the method of identification of ebb shoal outlines. On aerial photographs, the ebb shoal complex is best identified by the pattern of breaking waves. On a calm day, a minimal number of waves will break, and the aerial photograph would either show no shoal or the shoal would not be as easily identified, thus increasing the possibility for error. Such photographs were eliminated from analysis.

For each inlet, many aerial photographs of various years and various maturity stages were examined, and asymmetry indicator measurements made. Because the morphology of mature inlets varies through time about an assumed dynamic equilibrium, the asymmetry indicator measurements for each individual inlet were averaged. These average values were plotted in Figures 4, 5, and 7.

Identification of asymmetry indicators from nautical charts eliminates visual error in distinguishing the ebb shoal. National Ocean Service (NOS) nautical charts are comprised of measurement made at different times; however, they were considered acceptable to obtain asymmetry indicators. Only one set of indicators for each inlet examined was interpreted from the most recent nautical charts. For some inlets, both aerial photographs and nautical charts were available. In such case, measurements were taken from both. Therefore, only a single value of the three asymmetry indicators was measured and plotted. Distances to the offshore extent of the ebb shoal were identified on NOS charts through examination of the point at which the contour lines were oriented similar to offshore contours far from the inlet. This distance was visually clear and easily identified by assessment of the slopes of the contour lines.

Unrectified aerial photos of different scales were analyzed, and individual photograph scales were determined through comparison of distance between two stationary objects, such as jetties, to that same distance found on nautical charts. Uncertainties introduced for the distance measurements are estimated to be 25 to 150 m for the inlets examined, depending on the scale and on the distortion and parallax on the aerial photograph.

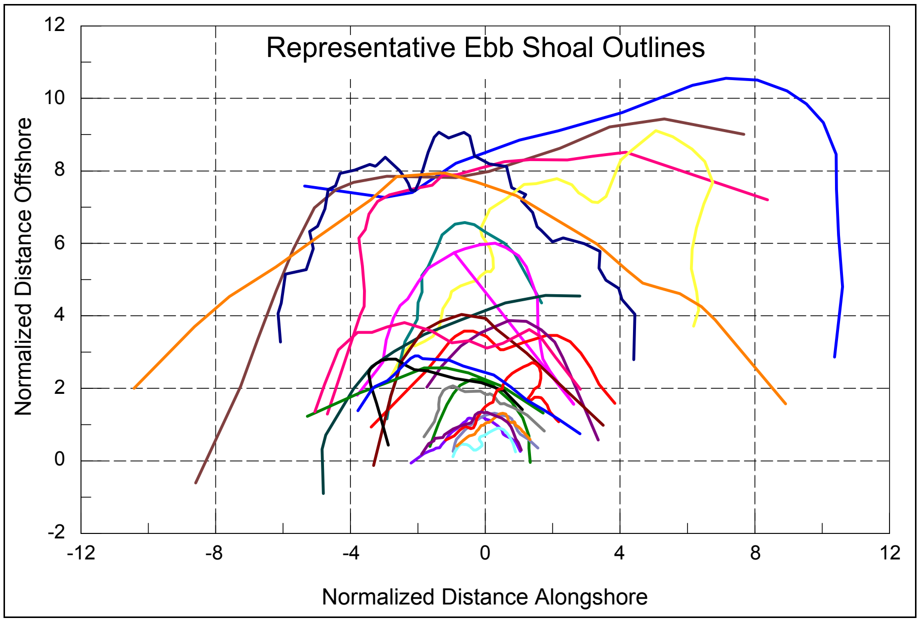

Figure 3. Digitized planform ebb shoal outlines (distances normalized by channel critical width)

ASYMMETRIES IN EBB-TIDAL SHOALS: Data from the ebb shoals are plotted in Figure 3 to fall into groups according to distance offshore, distance alongshore, and symmetry or asymmetry. The shoal outlines lying close to the origin exhibit symmetry about the y-axis and are similar in alongshore extent. A band of medium outlines is located between the smallest and largest ebb shoal outlines. These show larger normalized distance offshore and alongshore than the smaller outlines as well as exhibiting a greater variation of symmetry. The largest outlines have the greatest asymmetry. These inlet outlines show that the greater the distance offshore the greater the distance to the attachment bars.

Asymmetry in ebb tidal shoals occurs at inlets with a clear direction of net sediment transport. The ebb shoal profile at Old Topsail Inlet, NC, can be identified in Figure 3 as the blue profile that extends the furthest offshore. The outline indicates a great ebb shoal asymmetry in comparison to the other outlines in Figure 3. At Old Topsail Inlet, net longshore sediment transport is dominant to the south, which has given rise to the asymmetry of the shoal and a spit that has constricted the tidal channel, leading to a further asymmetrical tidal channel. Spit growth from the updrift side of the inlet, submerged at high tide, has constricted the channel, causing a stronger ebb jet to transport sediment further offshore. This spit growth pattern has contributed to the asymmetrical development of the ebb shoal complex. FitzGerald, Kraus, and Hands (2001) describe the migration process for this type of channel and asymmetrical shoal development in conceptual models of inlet migration and spit breaching.

Jarrett (1976) compiled previous work and assembled additional data to establish an inlet cross-sectional area - tidal prism relationship for 108 inlets on the Atlantic Ocean, Gulf of Mexico, and Pacific Ocean coasts of the United States. Shigemura (1981) found relationships with correlations between throat width and tidal prism at 231 natural bays on the major coasts of Japan. Walton and Adams (1976) related the volume of sediment in the ebb shoal to the inlets associated tidal prism and found increasing volumes of sediment with increasing tidal prisms. Based on laboratory experiments, Hayter et al. (1988) developed relationships indicating that the ebb jet flow governs ebb shoal size and shape. Gibeaut and Davis (1993) classified inlets based on the statistical analysis of ebb shoal outlines along the barrier island coast of west central Florida including Dunedin Pass, Longboat Pass, New Pass, Big Sarasota Pass, Midnight Pass, Stump Pass, Gasparilla Pass, Captiva Pass, and Redfish Pass. Relationships similar to those found for the ebb shoal, increasing shoal volume with increasing tidal prism, were found for the sediment volume contained within the flood shoal (Carr 1999). This previous work shows that the tidal prism is a decisive factor determining the morphology of a coastal tidal inlet, and it enters discussion of asymmetries given in the following paragraphs.

Distances to Attachment Bars: Asymmetry indicators were determined by subtracting half of the inlet critical width from the measurement of the distance from the channel center line to the updrift or downdrift attachment point.

Figure 4 plots distance to the downdrift attachment point versus tidal prism. Jarrett (1976) provides a listing of 108 inlets with known tidal prisms, as well as number of jetties. These inlets were analyzed here. Data points are denoted by closed symbols for nautical charts and by open symbols for aerial photographs. Consistency in notation is maintained through all plots of asymmetry indicators in this Technical Note. The inlets were distinguished by the number of jetties.

A trend of increasing distance to the downdrift attachment point with increasing tidal prism was identified and quantified for each category of number of jetties as well as for the entire data set. Regression lines were determined regardless of whether the measurement was taken from nautical charts or from aerial photographs. The regression lines (as well as the data points) are plotted in black for no jetties, in blue for one jetty, and in red for two jetties.

All trend lines in Figure 4 are governed by a power function as shown in Equation 2 with W_{A2} representing the distance to the downdrift attachment point as shown in Figure 2.

$$W_{A2} = a * P^{b} \tag{2}$$

The coefficients a and b, however, are distinct for each trend line associated with the individual sets of data points (Table 1). The table also provides the correlation coefficient (R^2) value for each regression line shown in Figure 4. The coefficients of Equation 2 differ depending upon the number of jetties at an inlet. If an inlet is to be modified, such as construction of a new jetty or alteration of an existing jetty, it can be expected that a change in morphologic symmetry will occur. Seabergh, Cialone, and Stauble (1996) and Stauble (1998b) document change in entrance channel location at Barnegat Inlet, NJ, in response to modification of the jetties there. More generally, changes to the entire ebb shoal complex and channel can be expected if one of the dynamic or static controlling factors changes.

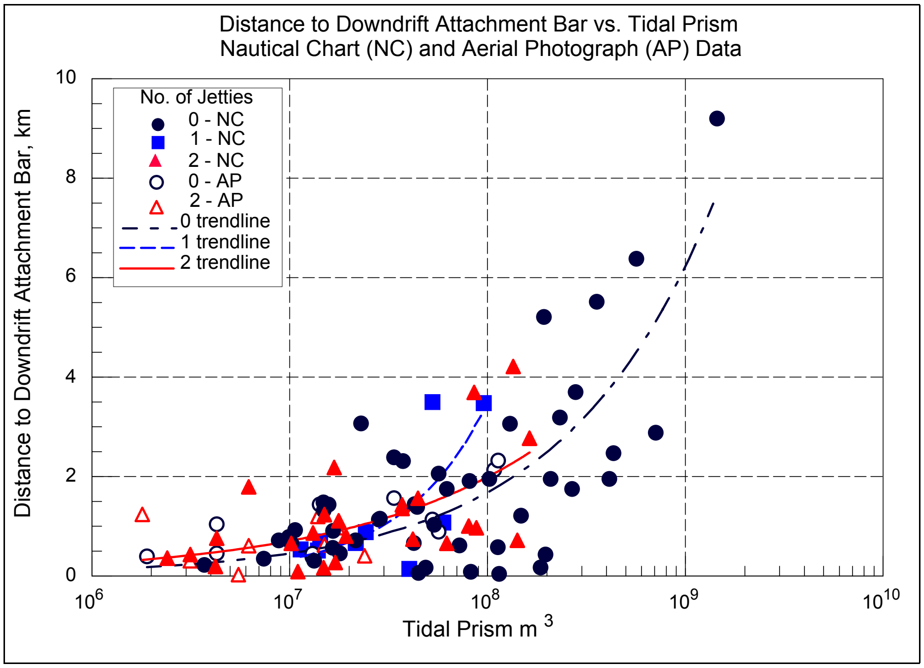

Figure 4. The distance W_{A2} vs. tidal prism for inlets examined

Table 1
Coefficients of Equation 2 for Trend Lines in Figure 4 (downdrift attachment bar)

Number of Jetties	*a*	*b*	R^2
0	4.8×10^{-5}	0.569	0.767
1	3.0×10^{-8}	1.011	0.765
2	5.0×10^{-4}	0.451	0.592

For distances to the downdrift attachment bar less than 2 km, Figure 4 indicates wide scatter over two orders of magnitude in the tidal prism. The scatter pertains mainly to inlets with either no jetties or with two jetties. At inlets with two jetties and small tidal prism, the bypassing bar or ebb shoal may attach directly to the jetties, such as the case of Boca Raton Inlet on the east coast of Florida; similar site-specific processes probably account for much of the scatter. At inlets without jetties, the phenomenon of atypically small distance to the attachment bar for the associated tidal prism may have several causes. One cause is discussed here by the specific example Oregon Inlet, NC. This inlet has a distance to the downdrift attachment bar less than 1 km but a tidal prism greater than 10^8 m^3.

Oregon Inlet, NC, exhibits an atypically small distance to the downdrift attachment bar in relation to the tidal prism. A terminal groin was constructed on the south (downdrift side) in 1990. However, aerial photographs of Oregon Inlet examined here predate 1990, and the inlet will be analyzed as an inlet without jetties. Oregon Inlet has two small channel margin linear bars. The property that is most likely limiting the distance from the inlet edge to the attachment bars are the downcoast and upcoast spits encroaching into the inlet. At Oregon Inlet, the ebb shoal-bypassing bar attaches to the southern spit near the inlet. Sediment from the spits becomes entrained in the ebb jet and as the spits migrate into the inlet the attachment bars move toward the inlet as well. Two jetties are proposed at Oregon Inlet (Miller, Dennis, and Wutkowski 1996) whose implementation will alter development of the ebb shoal, morphologic asymmetry, and sediment bypassing.

Distance to updrift attachment points is plotted against tidal prism in Figure 5, which shows patterns similar to those in Figure 4. Distance to the updrift attachment point from the inlet edge increases with increasing tidal prism for any number of jetties, and a comparable scatter of prism ranges under the 2-km distance to the attachment bar observed.

Figures 4 and 5 show that inlets with no jetties tend to form more distant attachment points than those with jetties. The trend toward greater scale is attributed to the fact that unjettied navigable inlets such as Willapa Bay, WA and San Francisco Bay, CA, are larger than typical jettied inlets. For these large inlets, jetties are unnecessary or infeasible.

Regression lines were determined for the updrift attachment bars (Figure 5) similar to the method for downdrift attachment bars (Figure 4). Table 2 gives the coefficients and R^2 values associated with Equation 2 with W_{A2} replaced by W_{A1}, the distance to the updrift attachment bar shown in Figure 2. There is reduced correlation between distance to the updrift attachment point and tidal prism shown in Table 2 at inlets with one jetty. Examination of the data in Figure 5 shows that at the inlets with only one jetty the jetty is consistently located on the updrift side of the inlet. This is a typical configuration because one purpose of a jetty is to reduce the flow of sediment into the inlet and to afford shelter from the predominant waves. This jetty placement may interrupt the ebb shoal complex at the attachment point and cause a shortened distance.

From Tables 1 and 2 it is evident that the downdrift asymmetry indicator (Figure 4) has stronger correlation with tidal prism than the updrift indicator. Available information was insufficient to examine the dependence of inlet asymmetry on magnitude and direction of the longshore sediment transport rate, expected to be a leading parameter and to be considered in future CIRP research.

The asymmetry of the main navigational channel may contribute to the data spread in Figures 4 and 5. A straight channel is expected to promote morphological symmetry and a reduced distance to the downdrift attachment point. Conversely, it is hypothesized that an asymmetrical channel with a smaller angle α between the thalweg and the shoreline (Figure 6) will result in an increased distance to the downdrift attachment point. This phenomenon is believed to act at Shinnecock Inlet, NY, where the ebb shoal is attached to the updrift shoreline at the jetty but has and extended distance to the downdrift attachment bar under conditions of a dominant direction of longshore transport. At Shinnecock Inlet the net west-directed longshore drift maintains the updrift attachment point close to the jetty. The strong net drift and, possibly, migration of the ebb jet (Militello and Kraus 2001) promote an asymmetrical channel alignment and increase the distance to the downdrift attachment point. Additionally, the longer length of the east jetty compared to that of the west jetty may contribute to the inlet asymmetry.

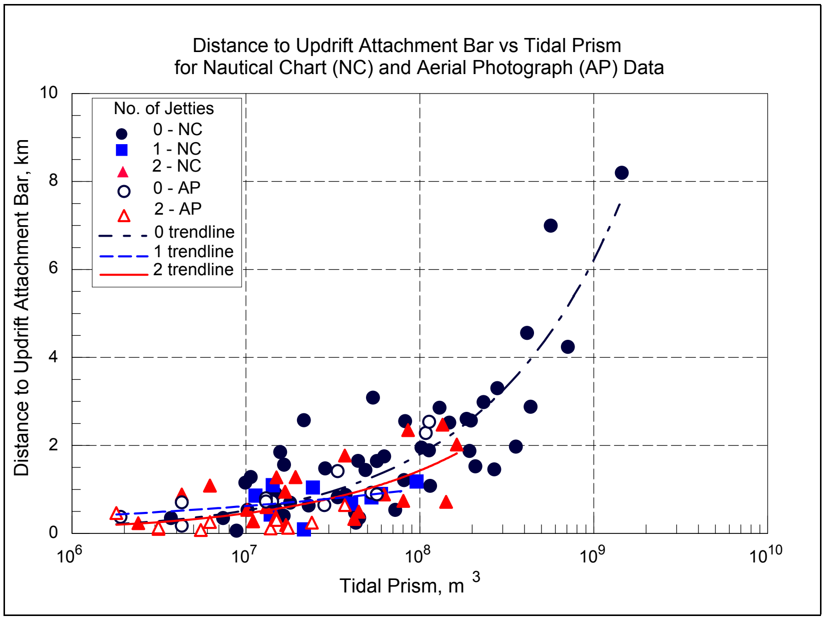

Figure 5. The distance W_{A1} vs. tidal prism for inlets examined

Table 2
Coefficients of Equation 2 for Trend Lines in Figure 5 (updrift attachment bar)

Number of Jetties	a	b	R^2
0	9.0×10^{-5}	0.539	0.86
1	2.01×10^{-2}	0.213	0.345
2	1.58×10^{-4}	0.495	0.649

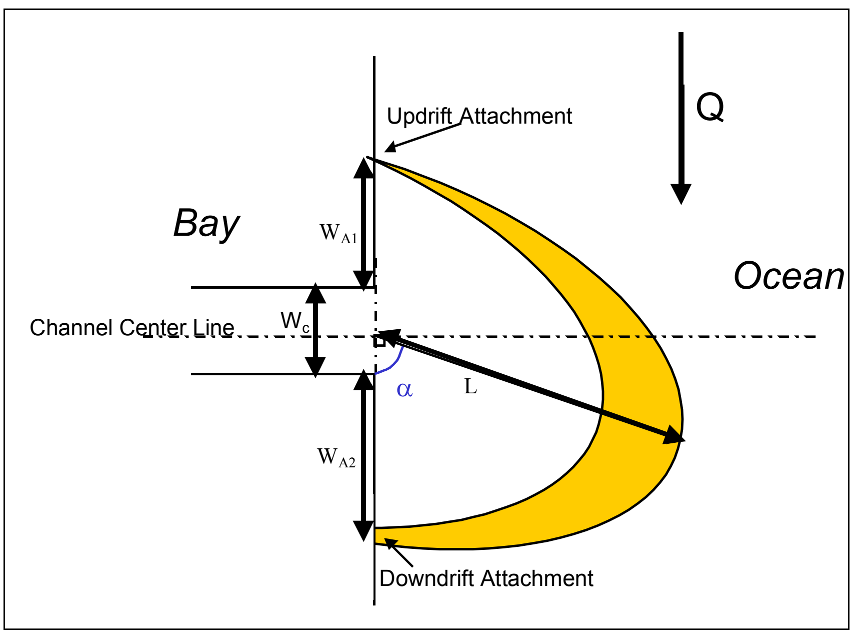

Figure 6. Asymmetrical ebb shoal with inlet angle definition

Seaward Extent of the Ebb Shoal: Magnitude of tidal prism, confinement of the ebb jet by jetties, and slope of the nearshore shelf in great part determine the offshore extent of the ebb shoal. Deposition of sediment carried by the ebb current into the ebb shoal is enhanced through refraction of the waves around the ebb shoal complex, tending to generate a longshore current directed toward the inlet on both sides. The ebb shoal shelters the area behind it from waves, creating a zone of low wave energy where sediment can deposit (Dean and Walton 1973), so that formation of an ebb shoal creates a self-preserving mechanism. Hubbard, Oertel, and Nummedal (1979) found that an ebb shoal developed at wave-dominated inlets lies closer to the inlet opening than the ebb shoal at a tide-dominated inlet. Ebb shoals formed on low-wave energy or tide-dominated coasts are longer and narrower with a more defined ebb channel and terminal lobe (Hayter et al. 1988).

The distance from the shoreline to the furthest seaward extent of the ebb shoal was determined through examination of the breaking wave pattern in aerial photographs. On nautical charts, the furthest seaward point of the ebb shoal was identified through bathymetric contours. The distance from the shoreline to the furthest seaward extent of the ebb shoal increases with increasing tidal prism (Figure 7). Although a clear visual trend exists, inlets with ebb-shoal offshore distances less than 2 km are found under a wide range of tidal prisms. Table 3 lists the coefficients of the trend lines in Figure 7 as given by Equation 2. In Equation 2, W_{A2} was replaced with the variable L defined pictorially in Figure 2.

Static factors controlling the asymmetry of the ebb shoal include the length and condition of the jetties. At a mature inlet with large longshore sediment transport, it is expected that the greater the distance the jetties extend offshore, the greater distance to the offshore terminus of the ebb shoal. Consequently, the more seaward ebb shoal will produce a greater distance to the downdrift and updrift attachment bars. However, it is feasible that in some situations the jetties are sufficiently long and, possible, relatively closely spaced such that the resultant ebb shoal can never form bypassing bars; material comprising the shoal is jetted so far seaward that wave action cannot return it under typical wave conditions. This is the situation at Grays Harbor, WA. Seaward migration of the ebb shoal alters the amount and location of sediment bypassing.

The condition of the jetties plays a role in determining asymmetry inlet morphology. If the jetties are permeable or low, sediment can enter the entrance channel. At impermeable jetties, the sediment accumulates on the updrift side of the structure until it can move around the tip of the jetty (jetty becomes fully impounded). An impermeable jetty will be a more effective sand by-passer to the downdrift shoreline because more of the sediment will be transferred from the updrift shoreline through the ebb shoal and ultimately deposit on the downdrift shoreline.

The relationships developed in this Technical Note for estimation of asymmetry indicators may assist in preliminary study for the design and maintenance of inlet navigational channels. Equation 2 may be employed, as part of an evaluation plan, if the addition or modification of jetties is being considered. In addition, these observations may be beneficial in estimating required bypassing and optimal location for placement of dredged material on the downdrift beach.

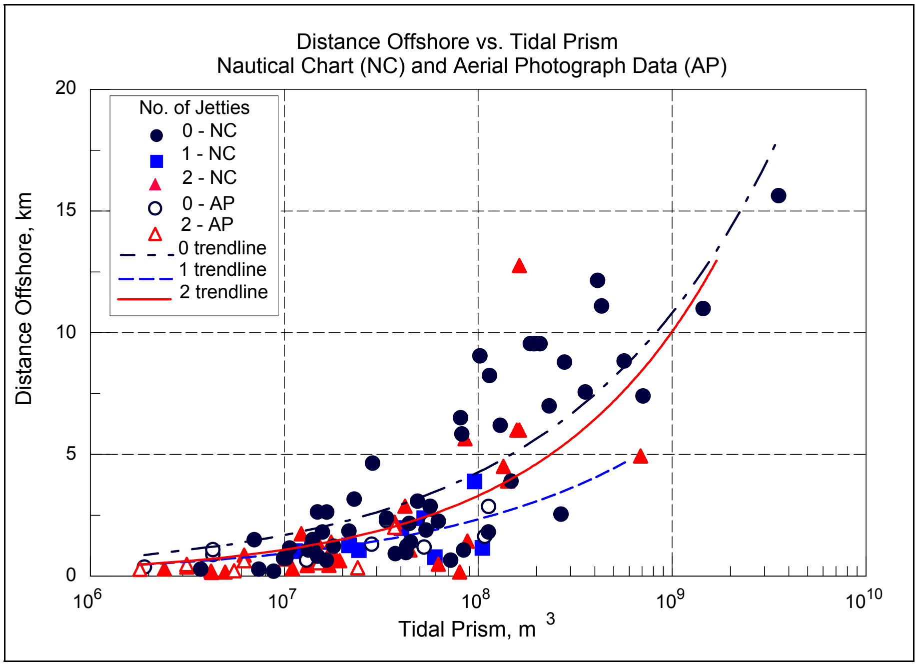

Figure 7. Distance from shoreline intersection with channel center line to most offshore point of the ebb-tidal shoal (*L*)

Table 3
Coefficients of Equation 2 for Trend Lines in Figure 7 (most offshore distance of ebb shoal)

Number of Jetties	*a*	*b*	R^2
0	$2.5x10^{-3}$	0.404	0.839
1	$1.5x10^{-3}$	0.399	0.536
2	$5.0x10^{-4}$	0.483	0.692

Temporal Changes: Not all inlets have achieved a dynamic equilibrium (changing only slightly with changes in impressed forces). The morphology of some inlets may undergo semi-periodic cycles or changes irregularly spaced in time (episodic changes, as triggered by a storm). At such inlets, it is difficult to predict, for example, the location of the natural channel that might be maintained by dredging. The temporal behavior of the ebb shoals is also of interest for the development of bypassing and causative relationships between dredging and process responses.

Time-varying behavior of inlets is illustrated in Figures 8 and 9 for St. Augustine Inlet, located on the northeast coast of Florida. The data were obtained through analysis of aerial photographs available from the mid 1940s to the present. The net direction of longshore transport on this coast is from north to south. St. Augustine Inlet was originally a natural inlet that migrated between two well-defined locations prior to stabilization in 1941, when the north jetty was constructed. By 1957, the old secondary inlet had closed. By 1970, a massive spit (named Conch Island) and located directly to the south of St. Augustine Inlet merged with surrounding Anastasia Island and Bird Island. Construction on the south jetty was completed in 1975 (Marino and Mehta 1986).

Absolute distances from the updrift inlet edge to the updrift attachment bar, W_{A1}, and the distance from the downdrift inlet edge to the downdrift attachment bar, W_{A2}, are plotted over time in Figure 8. The plot shows the distances to the downdrift attachment bar are greater than the distances to the updrift attachment bar for all years except 1949. There is a significant difference in the distances after 1957, when the south jetty was constructed, after which the distance to the downdrift attachment is consistently longer. Figure 8 shows a slight trend of increasing distance to the downdrift attachment bar over an interval of 60 years. In contrast, after 1955, the updrift attachment bar has remained in a relatively narrow band of locations.

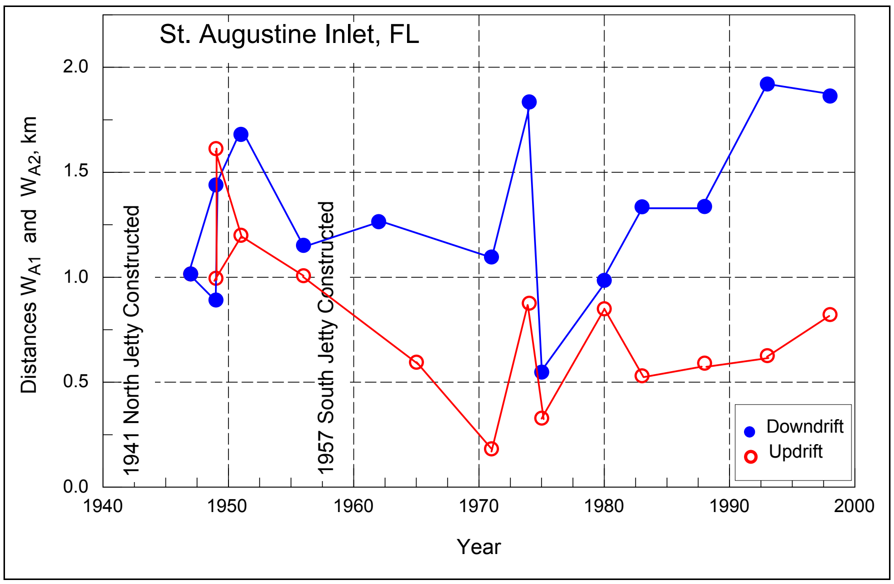

Figure 8. Distance to the downdrift and updrift attachment bars over time for St. Augustine Inlet

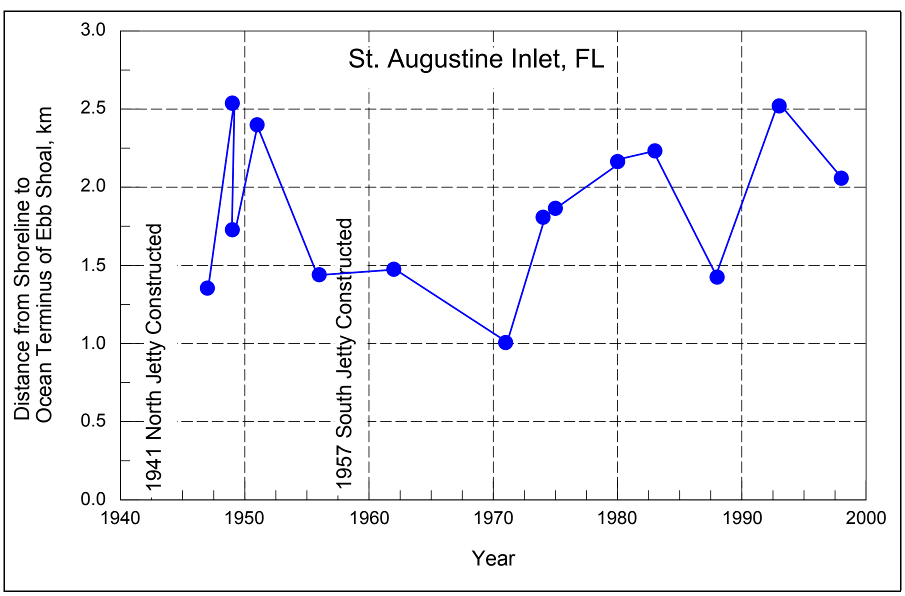

Figure 9. Distance to most seaward point of the ebb shoal over time for St. Augustine Inlet

ASYMMETRIES IN TIDAL CHANNELS: Asymmetries in the ebb shoal and channel alignment hold implications for operation and maintenance of inlet navigation projects. Placement of navigation channels in the preferred location and alignment of the natural channel may reduce dredging costs, a concept introduced by Price (1951), if navigability can be maintained.

Asymmetry in ebb-tidal shoal shape may also depend in part on the orientation of the entrance channel, and vice versa. Vincent, Corson, and Gingerich (1991) classified types of channel instabilities based on certain channel instability indicators. They noted that channel instabilities could cause asymmetries in the ebb shoal. FitzGerald, Kraus, and Hands (2001) noted the mechanism of sand transport at tidal inlets termed ebb-tidal delta breaching occurs at inlets where the main ebb channel is migratory to a downdrift orientation. Severe deflection of the channel causes a hydraulically inefficient situation, and the inlet discharge eventually forms a more efficient path through the old ebb delta. An orientation of the channel away from shore-normal may result from many factors. Accumulation or intrusion of sediment on one side of the ebb shoal can move a channel. Asymmetry of the flood shoal and branching ebb channels in the back bay can orient the jet at an angle. For example, at Ponce Inlet and at Murrells Inlet, SC, the main ebb channel has been deflected by the action of both processes, accumulation of sediment on one side of the channel and an asymmetrical orientation of the back bay channels (FitzGerald 1982). Recently, it was found that at Shinnecock Inlet, NY, eddies formed at jetties during ebb flow can migrate and redirect the jet, hence channel, persistently in one direction (Militello and Kraus 2001).

Although wave height is usually the main wave parameter determining the critical sea state for navigation (Demirbilek and Sargent 1999), the direction of waves with respect to vessel motion is also a controlling factor, even in milder wave conditions. In propagating toward an inlet on ebb tide, waves can steepen (Smith 1999; Larson and Kraus 2000), so it is safest for a vessel to meet the waves at a small angle, often on a sinuous course between wave crests and troughs. If the alignment of the navigation channel from shore-normal tends to direct vessels into the predominant waves, it may bring favorable navigation conditions, whereas if it places the vessels broadside to waves, the channel alignment would be unfavorable.

FitzGerald (1984) described a process of inlet migration at unjettied inlets that causes the ebb shoal to become asymmetrical. One side of an inlet may experience accretion caused by a differential in longshore transport. At the same time the other side of the inlet begins to erode owing to a decrease in sediment supply. Resultant changes in inlet entrance morphology alter the orientation of the ebb current. A reorientation of the main ebb channel occurs, caused by this new current pattern, and the ebb shoal planform is altered. FitzGerald, Kraus, and Hands (2001) introduce examples of sediment bypassing at natural, sandy inlets. The modes of bypassing found to occur often impact the main ebb channel at an inlet and create changes in the shape of the ebb shoal often causing a previously symmetric ebb shoal to take on an asymmetric shape even if this change is temporary. Mining of ebb shoals and possible modifications to the morphology have been discussed by Cialone and Stauble (1998).

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REFERENCES

Bruun, P., and Gerritsen, F. (1959). "Natural bypassing of sand at coastal inlets," *Journal of Waterways and Harbors Division* 85(4), 75-107.

______ . (1960). "*Stability of tidal inlets.*" North Holland Publishing Co., Amsterdam.

Carr, E. E. (1999). "An examination of flood deltas at Florida's tidal inlets," M.S. thesis, University of Florida, Gainesville, FL.

Cialone, M. A., and Stauble, D. K. (1998). "Historic findings on shoal mining," *Journal of Coastal Research* 14(2), 537-563.

Dean, R. G., and Walton, T. L. (1973). "Sediment transport processes in the vicinity of inlets with special reference to sand trapping," *Estuarine research.* L.E. Cronin, ed., Academia Press, Inc., New York, 129-149.

Demirbilek, Z., and Sargent, F. (1999). "Deep-draft coastal navigation entrance channel practice," Coastal Engineering Technical Note CHETN I-63, U.S. Army Engineer Research and Development Center, Vicksburg, MS. (*http://chl.wes.army.mil/library/publications/chetn*)

FitzGerald, D. M. (1982). "Sediment bypassing at mixed energy tidal inlets," *Proceedings 18th Coastal Engineering Conference*, ASCE, 1,094-1,118.

______ . (1984). "Interactions between the ebb-tidal delta and landward shoreline: Price Inlet, South Carolina," *Journal of Sedimentary Petrology* 45(4), 1,303-1,318.

FitzGerald, D. M., Kraus, N. C., and Hands, E. B. (2000). "Natural mechanisms of sediment bypassing at tidal inlets," ERDC/CHL CHETN-IV-30, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Gaudiano, D. J., and Kana, T. W. (2001). "Shoal bypassing in mixed energy inlets: Geomorphic variables and empirical predictions for nine South Carolina inlets," *Journal of Coastal Research* 17(2), 280-291.

Gibeaut, J. C., Davis, R. A. (1993). "Statistical classification of ebb-tidal deltas along the west-central Florida coast," *Journal of Coastal Research* SI 18, 165-184.

Hayter, E. J., Hernandez, D. L., Atz, J. C., and Sill, B. L. (1988). "Study of ebb tidal shoal dynamics," *Proceedings, Beach Preservation Technology,* 365-374.

Hubbard, D. K., Oertel, G., and Nummedal, D. (1979). "Development of tidal inlet sand bodies," *Journal of Sedimentary Petrology* 49, 1,073-1,092.

Jarrett, J. T. (1976). "Tidal prism-inlet area relationships," U.S. Army Corps of Engineers, GITI Report 3.

Kraus, N. C. (2000). "Reservoir model of ebb-tidal shoal evolution and sand bypassing," *Journal of Waterway, Port, Coastal and Ocean Engineering* 126(6), 305-313.

Kraus, N. C., and Rosati, J. D. (1998). "Interpretation of shoreline-position data for coastal engineering analysis," Coastal and Hydraulics Engineering Technical Note CHETN-II-39, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Larson, M., and Kraus, N. C. (2000). "Enhancements of the numerical model of the longshore current NMLONG to include interaction between currents and waves (NMLONG-CW)," Coastal and Hydraulics Engineering Technical Note IV-25, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Marino, J. N., and Mehta, A. J. (1986). "Sediment volumes around Florida's east coast tidal inlets," University of Florida Report Number UFL/COEL-86/009, University of Florida, Gainesville, FL.

Militello, A., and Kraus, N. C. (2001). "Shinnecock Inlet, New York, site investigation: Report 4, evaluation of flood and ebb shoal sediment source alternatives for the west of Shinnecock interim project, New York," Technical Report, ERDC/CHL-98-32, Report 4, Coastal Inlets Research Program, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Miller, H. C., Dennis, W. A., and Wutkowski, M. J. (1996). "A unique look at Oregon Inlet, NC USA," *Proceedings 25th Coastal Engineering Conf*erence, ASCE, 4,517-4,530.

Oertel, G. F. (1975). "Ebb-tidal deltas of Georgia estuaries." *Estuarine research*, *Volume II, geology and engineering.* L.E. Cronin, ed., Academic Press, NY 267-276.

Price, W. A. (1951). "Reduction in maintenance by proper orientation of ship channel through tidal inlets," *Proceedings of Second Conference on Coastal Engineering*, Council on Wave Research, The Engineering Foundation, 243-255.

Seabergh, W. C., Cialone, M. A., and Stauble, D. K. (1996). "Impacts of inlet structures on channel location," *Proceedings 25th Coastal Engineering Conference*, ASCE, 4,531-4,544.

Shigemura, T. (1981). "Tidal prism-throat width relationships of the bays of Japan," *Shore and Beach*, 49(3), 34-39.

Smith, J. M. (1999). "Wave breaking on an opposing current," Coastal and Hydraulics Engineering Technical Note IV-17, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Stauble, D. K. (1998a). "Techniques for measuring and analyzing inlet ebb-shoal evolution," Coastal and Hydraulics Engineering Technical Note IV-13, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

______ . (1998b). "Evaluation of pre- and post-jetty inlet shoal evolution." *Proceedings of the 1998 National Conference on Beach Preservation Technology*, 169-184.

Stauble, D. K., and Morang A. (1992). "Using morphology to determine net littoral drift directions in complex coastal systems," Coastal and Hydraulics Engineering Technical Note II-30, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Vincent, C. L., Corson, W. D., and Gingerich, K. J. (1991). "Stability of selected United States tidal inlets," U.S. Army Corps of Engineers, GITI Report 21.

Walton, T. L., and Adams, W. D. (1976). "Capacity of inlet outer bars to store sand," *Proceedings 15th Coastal Engineering Conf*erence, ASCE, 1,919-1,937.